Report 2225

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DAVID TAYLOR MODEL BASIN
WASHINGTON, D.C.

DEPARTMENT OF THE NAVY

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SURFACE WAVES GENERATED BY SUBMERGED RANKINE OVOIDS STARTING FROM REST

by

D. A. Shaffer

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HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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SURFACE WAVES GENERATED BY SUBMERGED RANKINE OVOIDS STARTING FROM REST

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ONR PO-5-0065
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ABSTRACT

Two Rankine ovoids were towed beneath the surface of a large body of water at several speeds and depths. The surface disturbance was measured both on and off the centerline of travel. The results of these tests were then compared with existing theoretical wave height predictions.

ADMINISTRATIVE INFORMATION

This study was initiated by Bureau of Ships letter S-Cutwater, Serial 360-005988 of 15 March 1960, and completed under Office of Naval Research Project Orders PO-5-0065 dated 16 October 1964 and PO-6-0062 dated 26 October 1965.

INTRODUCTION

An object traveling on or close to the free surface of a body of water produces a disturbance known as the Kelvin wake. The wave patterns produced have been studied by many investigators since Lord Kelvin[1] first formulated the theory of a wave train due to a moving pressure point on the free surface. Theoretical developments for predicting the wave height produced by simple hydrodynamic bodies, which can be represented by source and doublet distributions, can be found in the literature.[2–4] Yim[5] recently programmed the steady wave profile generated by a submerged body for a high-speed computer. It is only recently, however, that instrumentation capable of making accurate water wave measurements has been developed.

All the wave height measurements which have been made at the Taylor Model Basin have been done with a Rankine ovoid as the submerged body. This body is generated mathematically by a single source-sink pair in a moving stream. Therefore, the wave pattern is easily obtained mathematically once the wavemaking of a single source is known.[6]

The difficulty in measuring the Kelvin wake is a function of the wave height generated. The smaller the amplitude, the more difficult it becomes to measure the wave train. Moreover. one must have a steady reference from which to measure these wave heights. These measurements are practically impossible to make in an outdoor body of water, and most indoor facilities are too small. It takes a long length of run to establish a wave pattern of a submerged body and a wide body of water to avoid interference from wall reflections. The Maneuvering and Seakeeping Facility (MASK) at the Model Basin is probably the only facility in the country where the measurements can be made successfully. Even there, only a small portion of the wave pattern can be obtained.

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[1]References are listed on page 27.

In 1961, Ralston[6] built a towing rig for the MASK facility and made the first attempts to measure the wave pattern generated by a submerged Rankine ovoid. He failed to obtain reliable wave measurements because of the limitations of his measuring equipment and because no systematic investigation was made of transient wave effects. The capacitance-type wave height probes used by Ralston proved to be unsatisfactory because of contamination and the meniscus effect of the probe wire.

With the development of the sonic wave height transducer at St. Anthony Falls Hydraulic Laboratory and the modifications made by the Taylor Model Basin, it has become possible to measure waves as small as 0.01 in. With this instrumentation, Livingston of the Model Basin made the first successful wave height measurements under controlled conditions by towing a 9-ft-long Rankine ovoid.* Furthermore, he carried out a systematic investigation to eliminate transient effects from the wave train.

Although the MASK facility allows a 225-ft length of travel for the ovoid, there was barely time for a steady-state wake to develop before the ovoid had to stop. Thus, in order to construct a wave profile in a coordinate system which moved with the body, Livingston found it necessary to make many test runs, measuring the wave profile at different points in the basin. In this manner, he obtained a valid profile which included the Bernoulli hump over the body and about three crests in the trailing wave pattern. After about five body lengths, the wave profiles were in an unsteady condition and did not lend themselves to correlation with the other test runs made. However, the wave patterns obtained were just long enough to show reasonable agreement with a stationary phase solution over the first two or three wave crests. Computations by Yim were not available at that time for comparing the near-field wave pattern with theory.

Under the Office of Naval Research Project Order PO-5-0065, the Model Basin was requested to extend the work of Livingston by constructing a smaller ovoid in order to obtain more wave crests in the steady-state pattern and to obtain measurements both off and on the centerline. As a result, a 4.5-ft Rankine ovoid was built and the wave patterns were measured along the centerline and at several athwartship distances for a number of operating conditions. The shorter body made it possible to double the number of wave crests in the steady-state pattern.

This report summarizes the work done at the Model Basin in measuring the Kelvin wake produced by Rankine ovoids. The wave height measurements constitute reliable data for evaluating theoretical analyses of the wavemaking of sources.

*Reported informally in Hydromechanics Laboratory Test Report 039-H-01.

ANALYTICAL BACKGROUND

RANKINE OVOID

A Rankine ovoid is the body formed by the stagnation streamline in a uniform flow about a source-sink pair oriented parallel to the flow; see Figure 1. The flow is in the negative x-direction, the source of strength $M/4\pi$ is located at $(c, 0)$, and a sink of strength $-M/4\pi$ is located at $(-c, 0)$. The equation of a Rankine ovoid may be written in the form

$$y^2 + \frac{M}{2\pi U}(\cos\theta_2 - \cos\theta_1) = 0 \qquad [1]$$

where the coordinate system is shown in Figure 1. The half breadth h and the half length ℓ of a Rankine ovoid are obtained from the following set of equations:[7]

$$(\ell^2 - c^2)^2 = c\ell\,\frac{M}{\pi U} \qquad [2]$$

$$\frac{2c}{\sqrt{h^2 + c^2}} = \frac{2\pi U h^2}{M} \qquad [3]$$

A table of offsets for a 7 to 1 Rankine ovoid is also included in Figure 1.

STATIONARY-PHASE WAVE HEIGHTS

The steady-state wavemaking of a source moving beneath a free surface in the region far downstream may be approximated by a stationary-phase expression. The accuracy of this approximation is poor near the body but improves as the downstream distance increases. From Equation [11] of Reference 5, the wave height ζ on the centerline at any distance R from the source is

$$\zeta = 4\,\frac{M}{U}\,(2\pi g/RU^2)^{1/2}\exp(-gf/U^2)\cos(gR/U^2 + \pi/4) \qquad [4]$$

where g is the acceleration of gravity,

U is the velocity,

M is the source strength, and

f is the submergence depth of the source.

The wave length of the waves on the centerline is

$$\lambda = 2\pi U^2/g \tag{5}$$

If the wave heights of the two singularities are added, the wavemaking of the Rankine ovoid has the nondimensional form

$$\frac{\zeta_{RO}}{f} = B(2\pi f/R)^{1/2} \sin\,(R/fF_f^{\,2} - 3\pi/4) \tag{6}$$

plus higher order terms in $1/R$.

$$B = \frac{8M}{f^2 U F_f} \exp\left(-\frac{1}{F_f^{\,2}}\right) \sin \frac{c}{fF_f^{\,2}} \tag{7}$$

R is now the distance to the center plane of the ovoid, and F_f is the depth Froude number.

The Froude number is defined as the ratio of the inertia to the gravity forces; the depth Froude number is

$$F_f = U/\sqrt{gf} \tag{8}$$

where U is the towing speed,

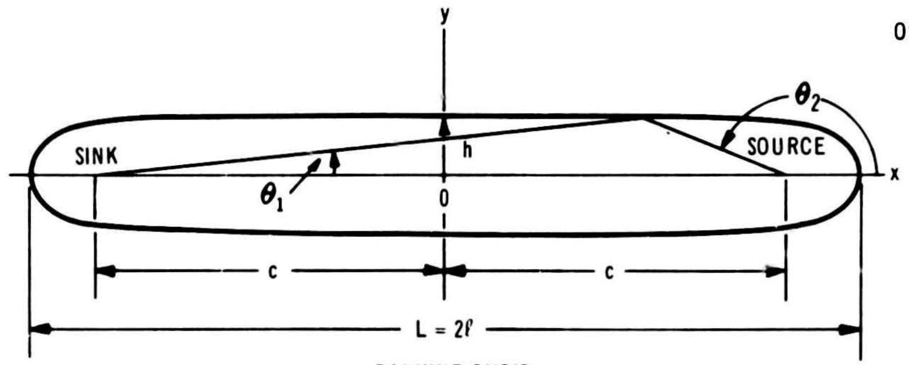
g is the acceleration of gravity, and

f is the submergence depth.

If B is plotted as a function of depth Froude number, the conditions for maximum and minimum wave heights can be seen in Figure 2. These minima can be calculated from Equation [7] by setting c/fF_f equal to $n\pi$. For c/f = 1.393, minimum wave heights occur at depth Froude numbers of 0.66, 0.470, 0.392, etc. as shown in Figure 2. The maximum heights are more complicated functions of the parameters.

TEST EQUIPMENT

Two Rankine ovoids were towed at several depths below the free surface in the MASK facility. This facility is 360 ft long, 240 ft wide, and 20 ft deep. The basin is large enough so that reflections from the walls did not interfere with the primary wake pattern. The ovoid



RANKINE OVOID

9.0-ft Ovoid	4.5-ft Ovoid
L = 9.0 ft	L = 4.5 ft
c = 4.18 ft	c = 2.09 ft
$\frac{M}{U} = 0.104\ \text{ft}^2$	$\frac{M}{U} = 0.026\ \text{ft}^2$

Offsets of a 7 to 1 Rankine Ovoid

x/ℓ	y/ℓ
0.0000	0.07144
0.0480	0.07138
0.0960	0.07118
0.1440	0.07104
0.1923	0.07094
0.2400	0.07084
0.2824	0.07040
0.3360	0.06949
0.3838	0.06735
0.4000	0.06600
0.4320	0.06133
0.4700	0.04944
0.4800	0.04033
0.4889	0.03122
0.5000	0.00000

Figure 1 – Rankine Ovoid Dimensions

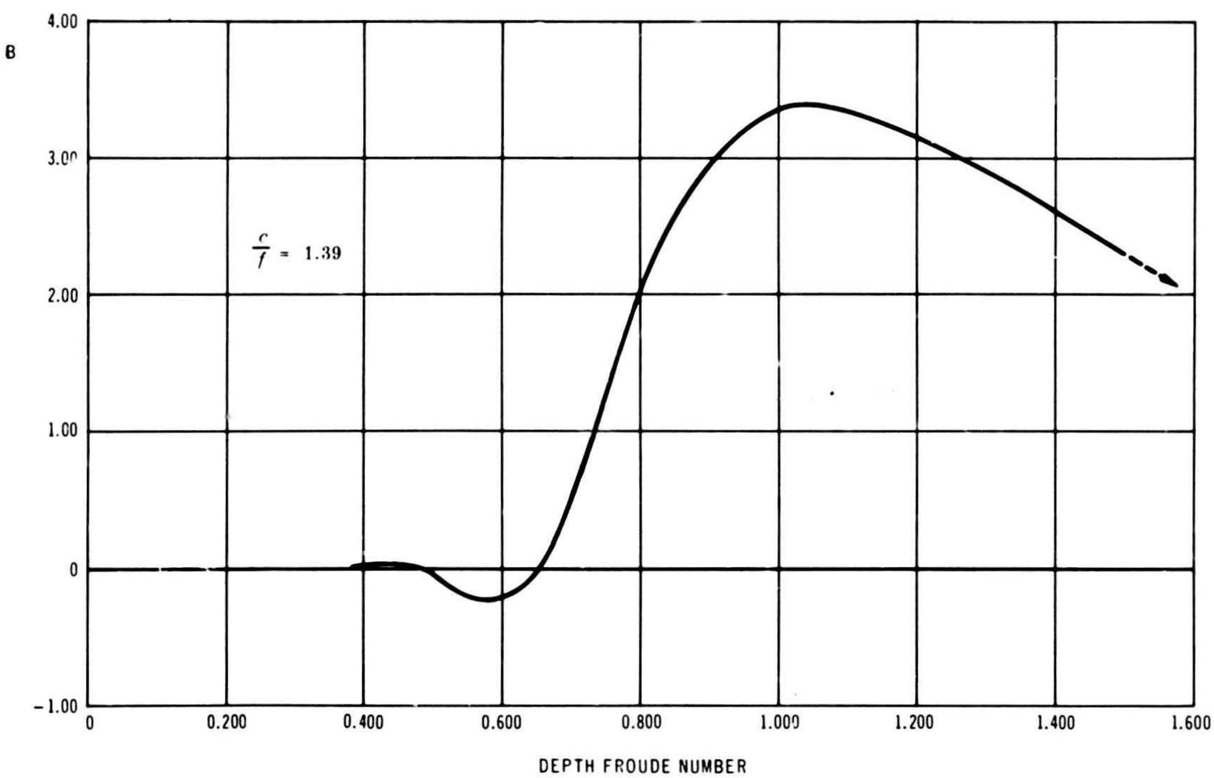


Figure 2 – Stationary-Phase Expression, *B*, as a Function of Froude Number

towing mechanism was supported by submerged towers near the ends of the basin. This permitted a 225-ft run of which approximately 20 ft was needed for accelerating and decelerating the model. Wave heights were measured on and off centerline from a carriage suspended from a bridge over the basin.

RANKINE OVOIDS

Two 7 to 1 Rankine ovoids which were ballasted and had zero buoyancy were used during the tests series. The 9.0-ft long ovoid was towed at a nominal depth of 3.0 ft, and the 4.5-ft long ovoid was towed at a nominal depth of 1.5 ft. Figure 1 shows the offsets from which the dimensions of the two ovoids can be obtained.

TOWING RIG

Support Tower

The towers were placed 250 ft apart on the bottom of the basin and were designed with a three-point support base to ensure against rocking on the slightly uneven floor of the facility; see Figures 3 and 4. The stability of the tower depended upon its gravitational weight because it was not permissible to anchor the towers to the basin floor. Each tower weighed approximately 3000 lb; this was sufficient to counter the overturning moment placed upon it by the cable system. As a safety measure, each tower was weighted with five 1500-lb weights at its base to provide an additional 7500 lb of ballast.

A crossbar, bolted to the face of each tower, supported the guide cables and towline pulleys. The crossbar could be positioned up and down the tower face in 6-in. increments which gave a range in depth of submergence of 0.5 to 15 ft. The outboard pulleys supporting the guide cables were adjustable in 2-in. increments, spanwise on the crossbar, to accomodate models up to 24 in. wide.

The crossbars of each tower were constructed of aluminum; this material was chosen partly for its corrosion-resistant properties and partly to lighten the bars for underwater adjustment purposes. The pulleys that operated underwater were made of stainless steel and rotated on bronze bearings. The structural steel members of the towers were painted with a corrosion-resistant paint. All of this equipment was in good condition after several years of submergence.

Guide Cables

The guide cables were 5/32-in. aircraft cable. Aircraft cable had a high tensile strength and could be stretched tightly to obtain a flatter catenary than possible with ordinary cable. The cable could also withstand long periods of submergence in water because it was made of a highly corrosion-resistant nickel-steel alloy.

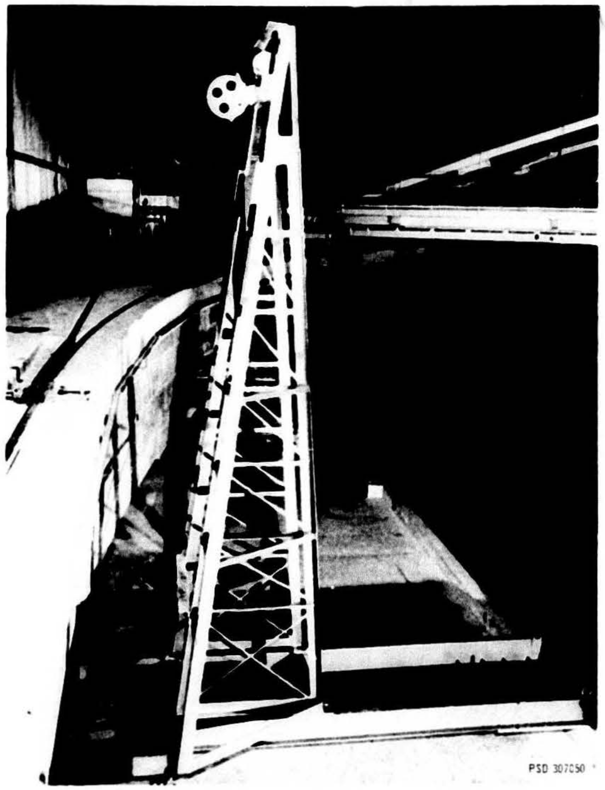


Figure 3 – Leaning Tower (Located at West End of the Basin)

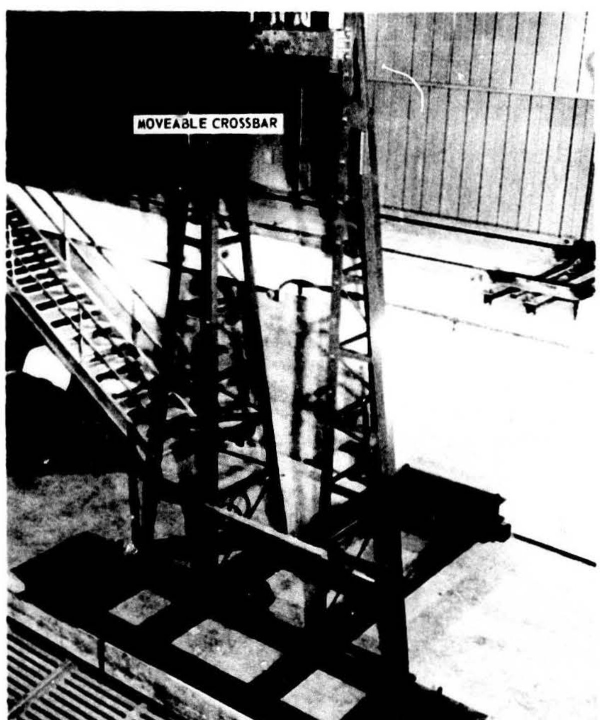


Figure 4 – Straight Tower (Located at East End of the Basin)

One end of each guide cable was anchored to a concrete wall at the end of the basin by a 15-ft piece of chain and a chain fall. The chain fall was used to slacken the cable when not in use, and the 15-ft piece of chain was sufficiently long to allow for adjustment of the guide cable length when towing at different depths. The other end of the cable hung over a pulley and had a steel bucket loaded with lead attached to it to keep the cable under constant tension during tests. In the present experiments, the cable was kept under 750 to 900 lb tension and had a sag of about 3 in. over the span of the test region. The Rankine ovoid was ballasted to neutral buoyancy and was attached to the guide cables by a set of stainless steel shoes with a teflon insert for bearings.

Towline

The towline was a continuous loop of 1/8-in. aircraft cable. The model had small eye bolts at either end for attachment to the free ends of the cable. A multiple-groove drive wheel and idler pulley system was used to drive the towline and keep slippage minimal when rapidly accelerating and decelerating the model. Measurements during the test indicated that on the average, this slippage was about 3 in. for each run. After four test runs, the idler pulley system had to be slackened and the towline line and model moved back to the reference position. The idler pulley system was also designed to serve as a tensioning device. The tension on the towline was kept at 600 lb at all times.

Apparatus for Determining Position and Speed of the Model

The drive wheel of the towline system was designed to turn off 3 ft of towline at each revolution, and a mechanical counter, geared to the drive wheel by a tachometer cable, provided visual monitoring of the model positions at all times. In addition, microswitches were closed at each revolution of the drive wheel by a cam mounted on the counter shaft. One microswitch was not sufficient to provide the accuracy needed, so two more switches were added to provide a switch closure for every foot of travel of the ovoid. The recorded signals from the microswitch and from a timer on the recorder were used to calculate the average velocity of the model during each test run. The recorded signal from the microswitch also provided a record of the distance traveled by the model within $\pm$ 6 in. so that the positions of the model could be synchronized with the position of the wave transducers.

An additional, and more accurate, method was used to check the position of the ovoid with respect to the carriage. A microswitch was covered with a waterproof plastic boot and mounted on a probe attached to the carriage. At each passage of the model, an aluminum arm on the model made contact with the flexible arm on the switch to provide a signal to the recorder. This switch was located 10 ft downstream from the wave probes.

Drive Mechanism

The drive mechanism was powered by a 5-hp, d-c electric motor with a gear reduction assembly that provided a towing speed range of 0 to 20 ft/sec. The system was controlled by a feedback-type power supply which maintained the motor speed within 0.5 percent of the desired setting. The motor was stopped by utilizing regenerative braking. A current limit adjustment switch allowed the starting and stopping acceleration to be preset to any desired value. A traveling-nut-type limit switch assembly, geared to the drive mechanism, provided automatic stopping of the model at any preselected point in the test run.

The drive mechanism and control console were mounted over the water on a platform resting on the beach at the end of the basin; see Figure 5. This arrangement allowed the operator to visually monitor the drive assembly during testing to ensure that everything was operating smoothly. Part of the platform was enclosed in a wire mesh cage to protect the operator in the event of cable breakage.

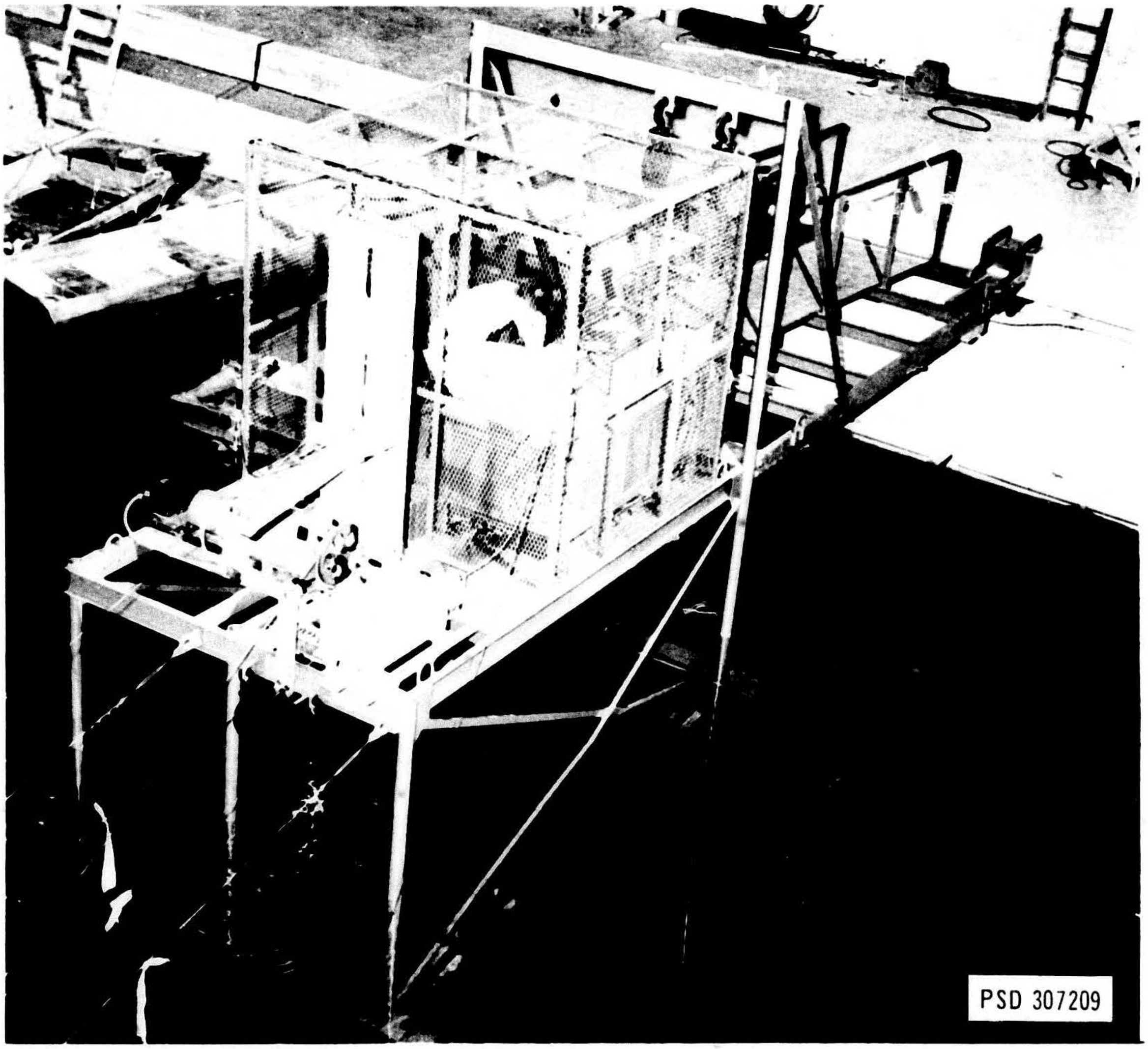
WAVE HEIGHT PROBES

Three types of wave height probes were used during the course of this investigation: capacitance, resistance, and sonic. Only the sonic type was completely satisfactory. The other two probes penetrated the water surface and their response was affected by surface contamination and by surface tension. At the time of Ralston's experiments, only the capacitance-type probe was available.[8] Both Livingston and the author used sonic-type probes which were developed at the St. Anthony Falls Hydraulics Laboratory.[9] Since these probes had to be widely spaced to avoid electrical interference, only two could be used in the experimental setup. In an attempt to increase the number of wave measurements which could be made per run, additional data were obtained with two resistance-type wave probes recently developed at the Model Basin. These probes proved to be difficult to balance, were nonlinear, and were subject to contamination. In the end, all the reported data were obtained with the sonic probes.

RECORDING EQUIPMENT

Analog outputs from the three types of wave height probes were recorded with a Series 350 Sanborn Recorder. A carrier amplifier system was used with the capacitance probes and a d-c coupling amplifier with the resistance probes. The sonic probes had their own built-in amplifier system.

In the tests with the 4.5-ft Rankine ovoid, the data were also recorded on DIDAS, a multichannel digital acquisition system.[10] These results were not useful for several reasons:


PSD 307209

the sampling rate of DIDAS conflicted with the pulse rate of the sonic transducer, a ground loop developed with the 300-ft transmission lines from the carriage to the recording station, and the signal-to-noise ratio was below tolerable limits.

TEST PROCEDURE AND RESULTS

Three separate tests were conducted with two sizes of Rankine ovoids in the MASK facility at the Model Basin. In the first two tests, Ralston[6] and Livingston[7] used a 9.0-ft, 7 to 1 ovoid. Ralston measured the surface disturbance both on and off the centerline of travel. Unfortunately he failed to recognize the importance of the transient effect (i.e., length of ovoid travel) on the wave profile and therefore the data were of little use. Livingston, on the other hand, foresaw this problem and was able to eliminate the transient effects of the wave profile and obtain a limited wave profile which moved with the body.

As a result of Livingston's work, it was discovered that a valid steady-state wake could be established for about one-half of the towed length of run of the body, thereby, significantly reducing the number of test runs needed to obtain a meaningful profile. Therefore, since gravity wave profiles are scaled with Froude number, it was postulated that a similar 4.5-ft Rankine ovoid, half the length of the original ovoid, would give a wake of twice the number of body lengths, in the same length of run.

The length of all the test runs was limited to 225 ft. The starting acceleration and deceleration distances were about 10 ft each. Therefore, the length of test run, for constant velocity, was about 205 ft. In all but a few tests, the model was allowed to travel the full 225 ft. The depth of the water in the basin during the test was 19 ft 11 in. and was kept at this depth within ± 1/8 in. During the course of the run, the depth variation of the model due to the sag in the tow cable was no more than ± 1.5 in. Figure 6 shows the tow cable catenary for the 4.5-ft ovoid.

9.0-FOOT, 7 TO 1 RANKINE OVOID

Livingston towed a 9.0-ft Rankine ovoid at several speeds and at a submergence depth of 3.0 ft and measured the centerline time history of the surface disturbance. Wave heights were measured with a sonic surface wave transducer, and the output of these gages was recorded on a Series 350 Sanborn Recorder. Despite the 150- to 180-ft runs, he found that only a limited portion of the wave train represented a steady-state condition and that measurements at a single point would not give a valid representation of the Kelvin wake for this ovoid. Therefore, it was necessary to construct a wave pattern which moved with the body by taking single wave height measurements from many test runs at finely spaced intervals over the distance. A wave pattern constructed in this manner increased in length as the time from the starting point was increased.

Figure 7 shows the growth of the centerline wave pattern of a Rankine ovoid towed at 10 ft/sec at a 3-ft submergence depth to the axis of the body.[7] After the body had traveled through a distance of 72 ft, the wave pattern was fully developed for two crests only. As time increased, the third crest continued to increase in amplitude and other crests began to develop downstream. After a run of 132 ft, steady-state conditions had developed up to the second and possibly the third crest.

4.5-FOOT, 7 TO 1 RANKINE OVOID

A 4.5-ft Rankine ovoid was constructed for the new series of tests. Tests were run at several velocities with the axis of the ovoid 1.5 ft below the free surface. Wave heights were measured with both sonic and resistance-type wave probes. The output of these transducers were recorded on a Series 350 Sanborn Recorder and on DIDAS.

The wave patterns were measured at five longitudinal stations approximately 48, 63, 95, 133, and 187 ft from the starting position of the model. Measurements were made at two lateral locations on each run. In one set of runs measurements were taken directly over the path of the model and 22.75 ft to beam. In the other set of runs the carriage was moved laterally, and measurements were taken 11.275 and 34.125 ft to beam. Figures 8 and 9 show the measuring stations and the locations of the wave-measuring probes with respect to the line of tow of the model. Extensive wave measurements were made at speeds of 6.0, 7.3, 9.0, and 10.0 ft/sec. Other wave measurements were made at towing speeds between 3.2 and 5.5 ft/sec. A total of 194 test runs were made. Representative data from these runs are presented in Figures 10 through 18; original data from some of these runs have been reported informally in Hydromechanics Laboratory Test Report 105-H-01.

Figures 10 through 18 show centerline and three off-centerline time-varying wave profiles produced at different towing speeds. These records were made at Measuring Station 4 which was between 130 and 135 ft from the start of the run. The longest steady-state wave pattern was obtained at this station. It became difficult to measure off-centerline data below velocities of 6 ft/sec.

As the model approached the centerline wave probe, the pressure built up over the nose of the model and a wave crest formed, known as the Bernoulli hump. As the model passed, the pressure became negative over the midsection and a wave train formed aft of the body. The wave crests in the wake immediately behind the model were usually the highest. The later crests decayed monotonically and became uniform in period far downstream. The height of the wave crests were functions of the towing velocity, submergence depth, body length, and displacement. Figure 17 shows the variation of the wave heights of the first and fifth centerline wave crests with velocity produced by the 4.5-ft Rankine ovoid at 1.5-ft submergence. The wave crests have maximum values at a velocity of 7.3 ft/sec which corresponds to a depth Froude number of 1.05.

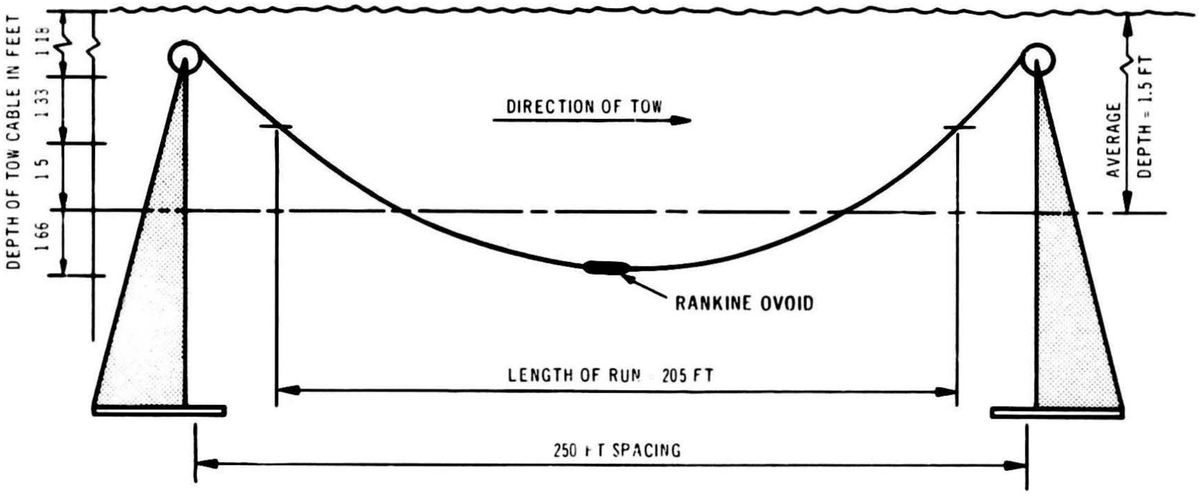


Figure 6 – Tow Cable Catenary with Zero Buoyancy Rankine Ovoid

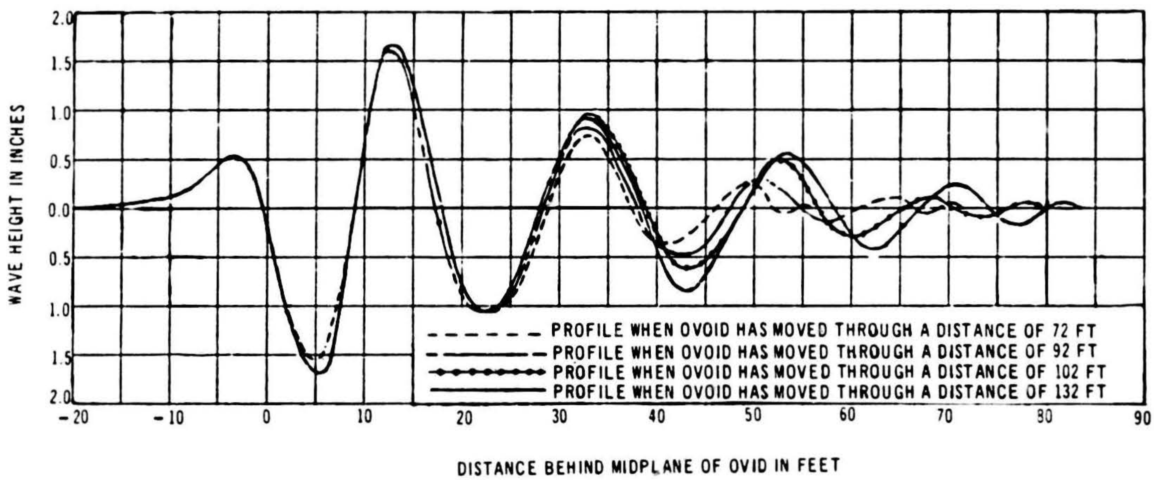


Figure 7 – Centerline Wave Profiles of a Rankine Ovoid as a Function of Length of Run

Ovoid length = 9 ft, submergence depth = 3 ft, U = 10 ft/sec, F_f = 1.02.

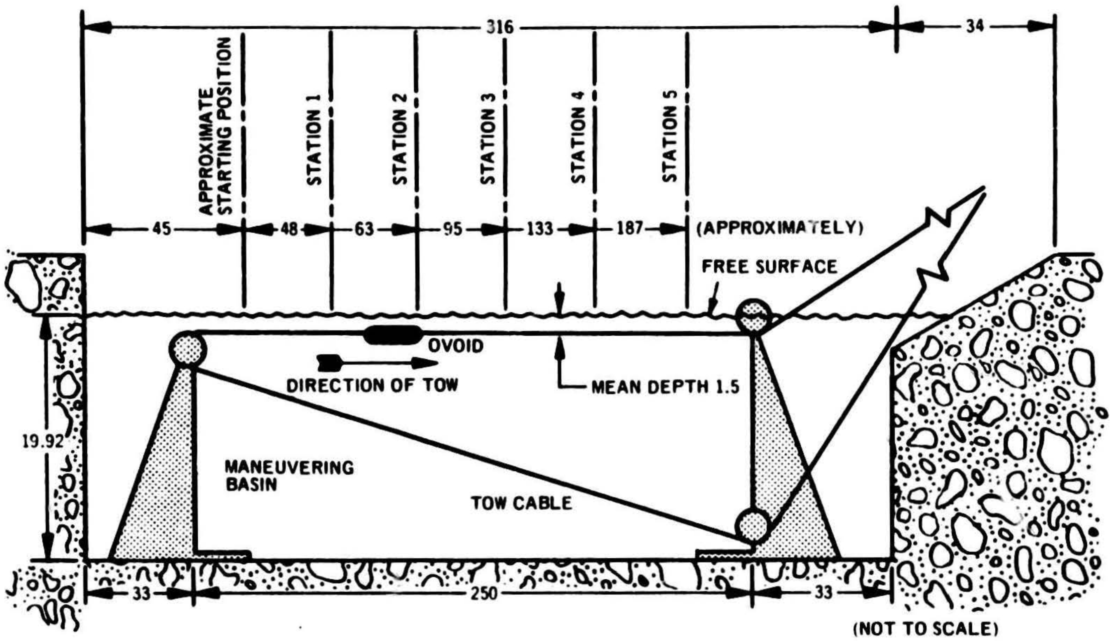


Figure 8 – Tow Cable and Model Location

All dimensions are in feet.

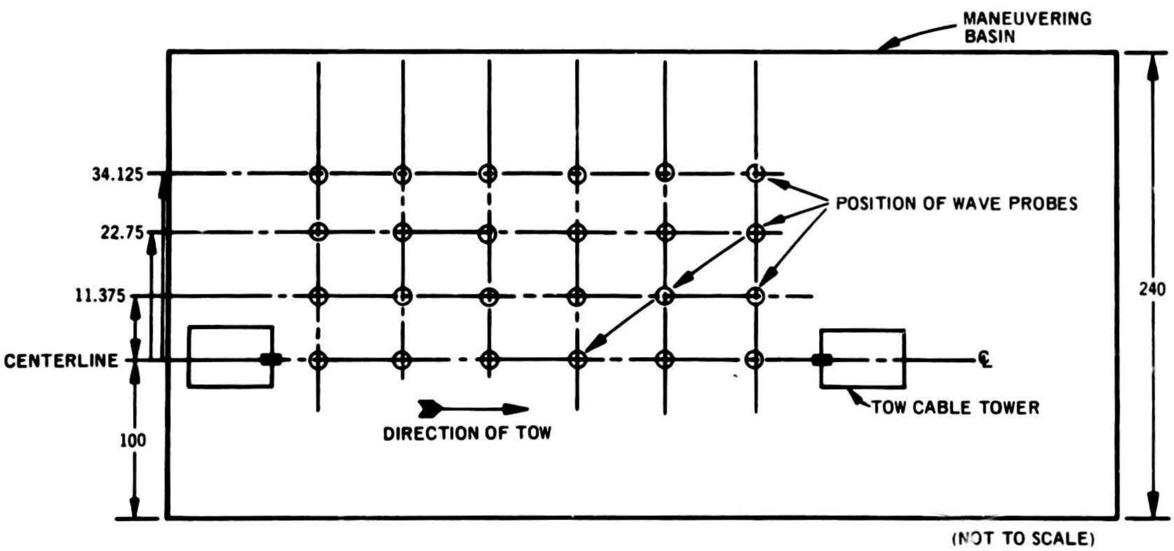


Figure 9 – Location of the Wave-Measuring Probes with Respect to the Line of Tow

All dimensions are in feet.

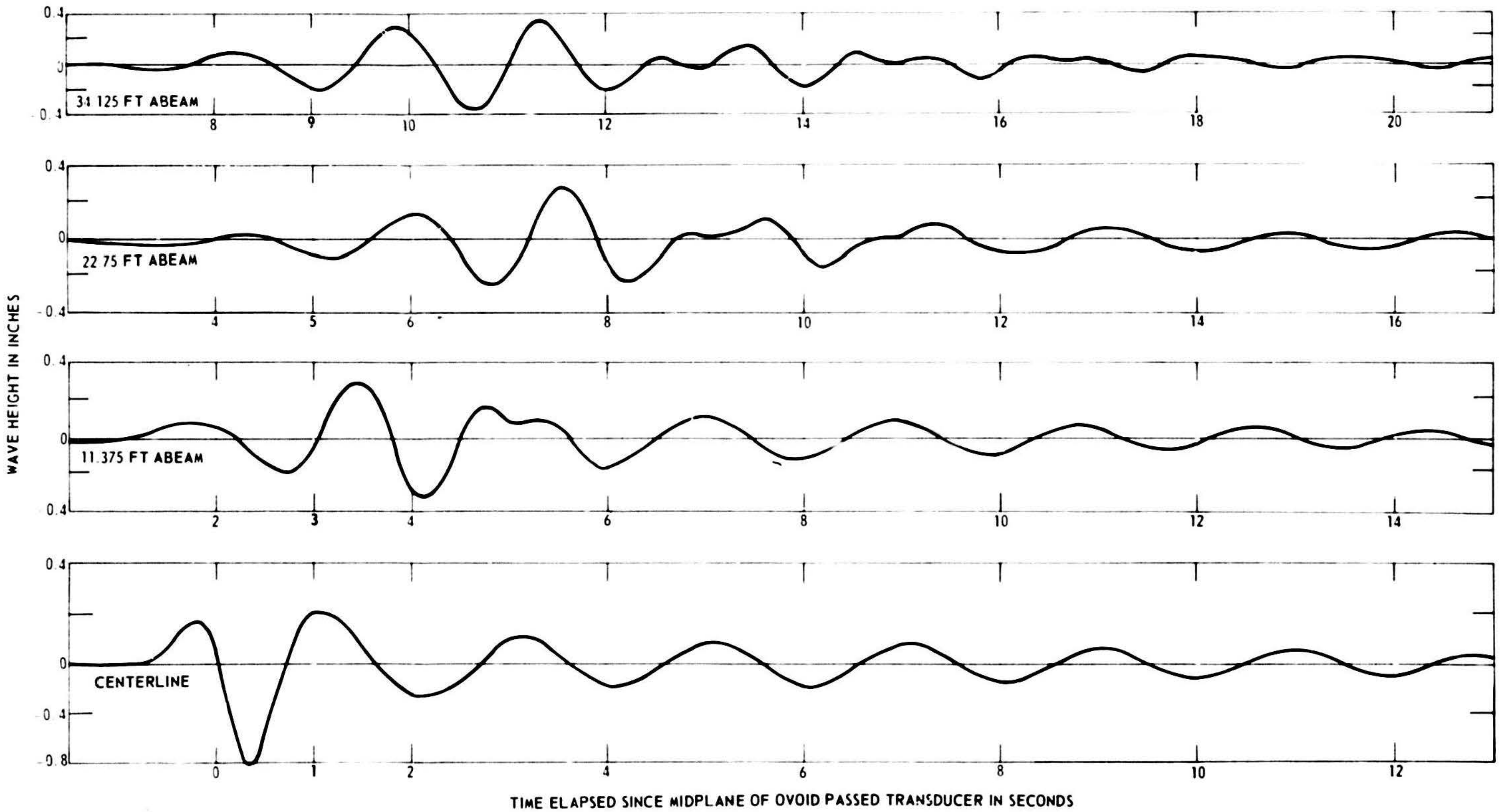


Figure 10 – Wave Heights of a Rankine Ovoid Towed at 10 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, F_f = 1.44, Measuring Station 4.

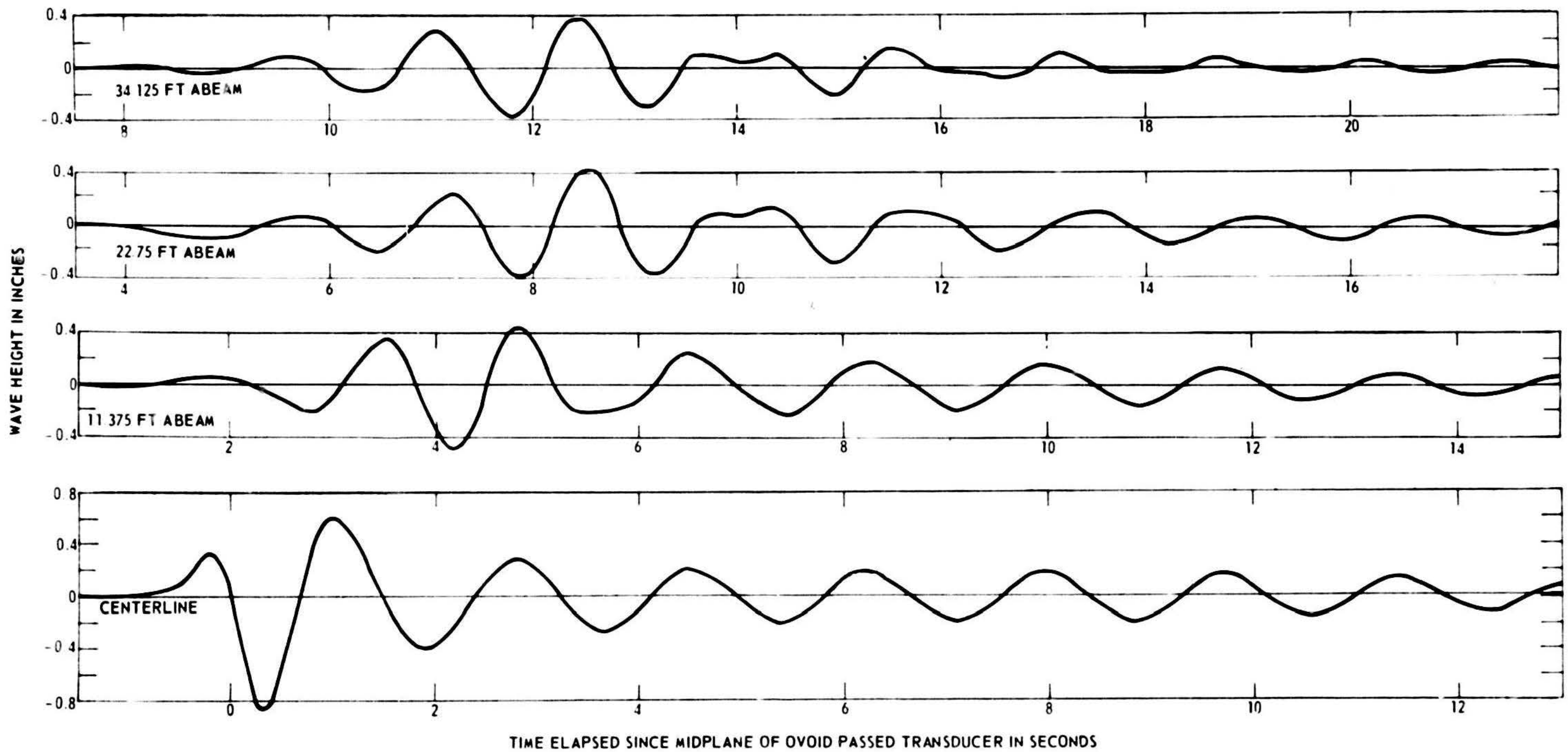


Figure 11 – Wave Heights of a Rankine Ovoid Towed at 9 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, F_f = 1.295, Measuring Station 4.

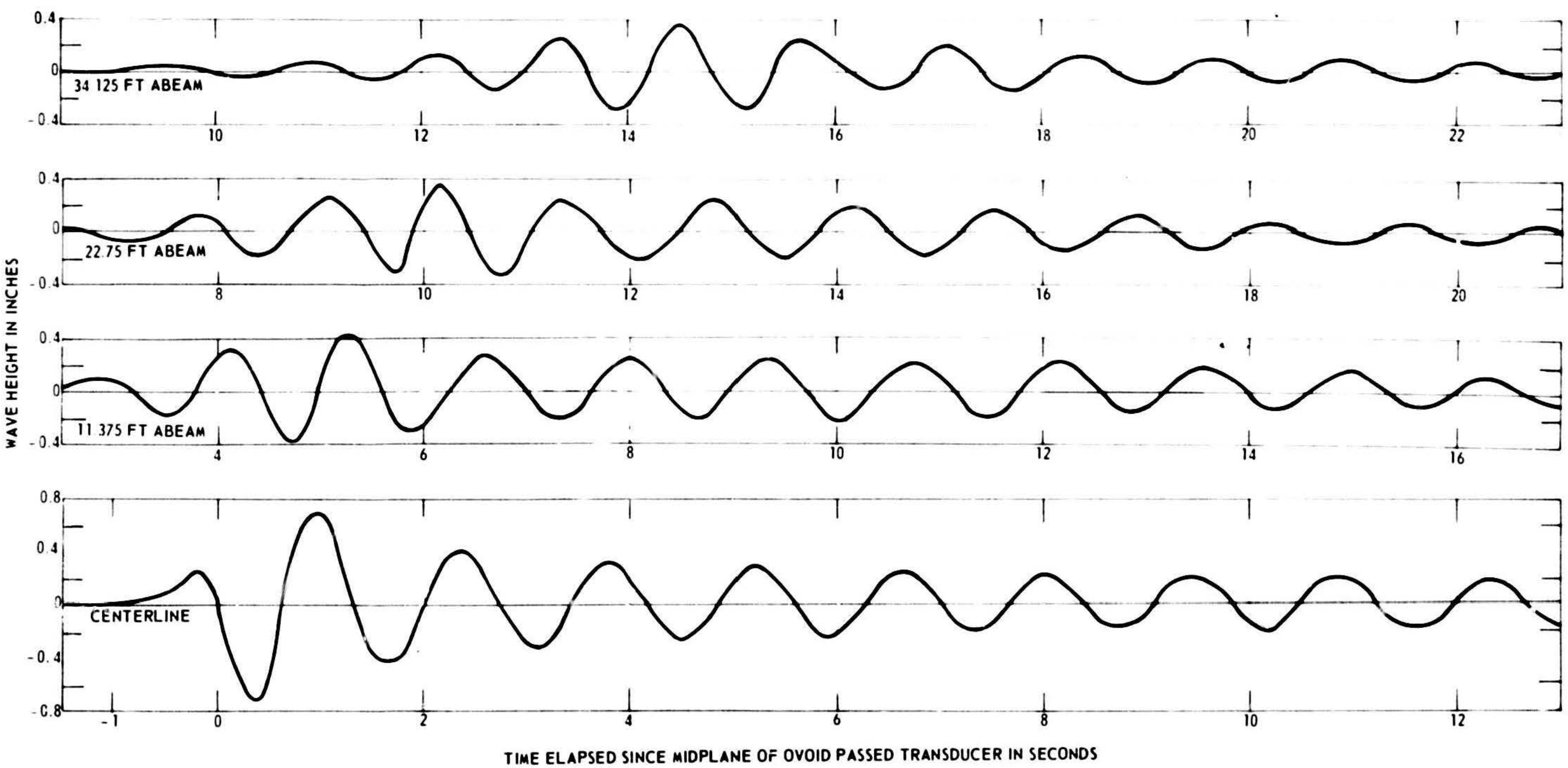


Figure 12 – Wave Heights of a Rankine Ovoid Towed at 7.3 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, F_f = 1.05, Measuring Station 4.

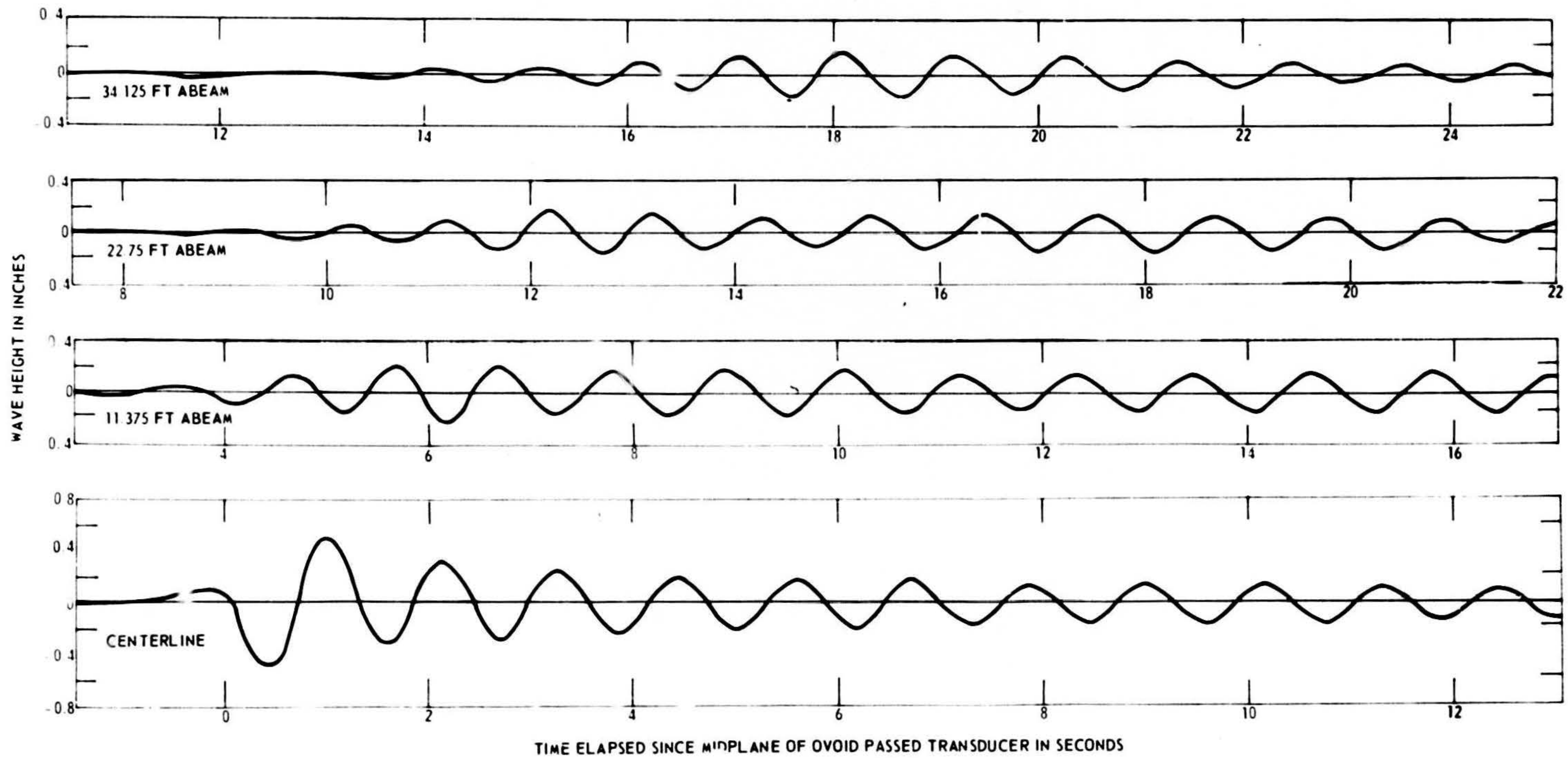


Figure 13 – Wave Heights of a Rankine Ovoid Towed at 6 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, F_f = 0.863, Measuring Station 4.

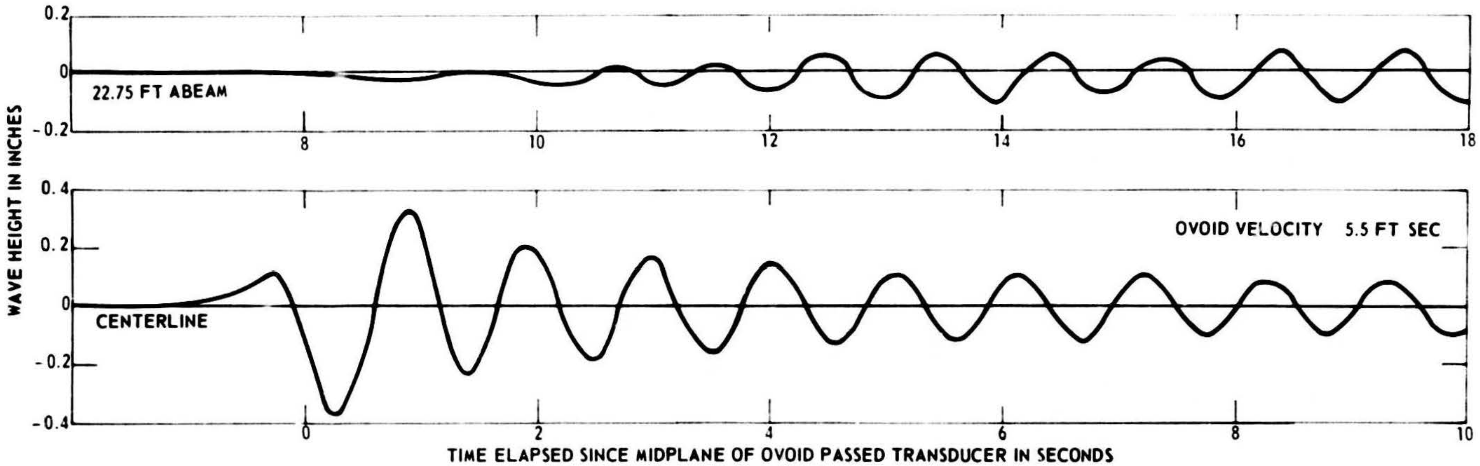


Figure 14 – Wave Heights of a Rankine Ovoid Towed at 5.5 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, $F_f = 0.79$, Measuring Station 4.

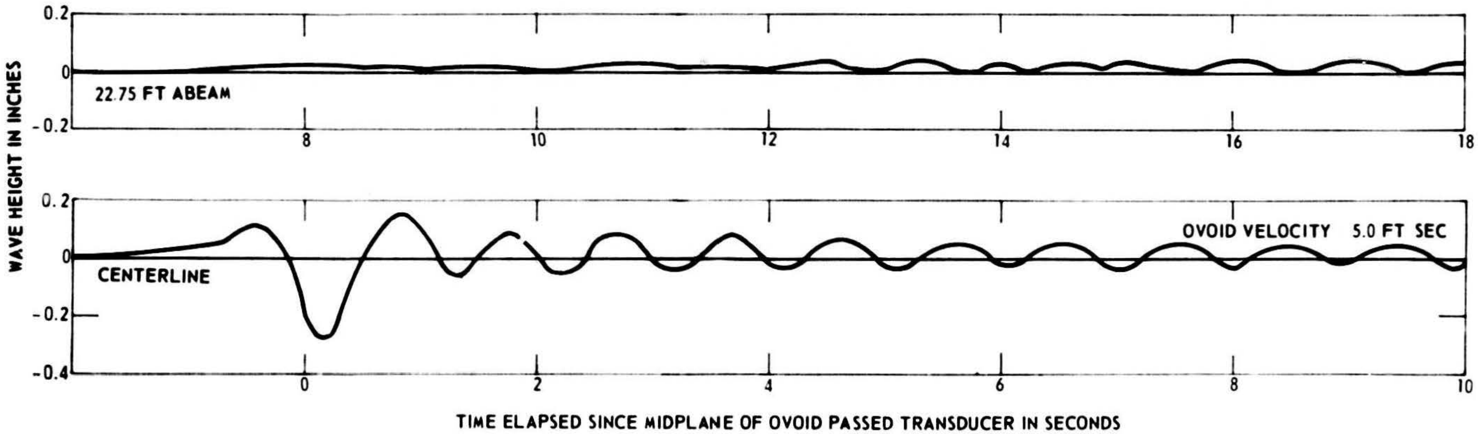


Figure 15 – Wave Heights of a Rankine Ovoid Towed at 5.0 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, $F_f = 0.72$, Measuring Station 4.

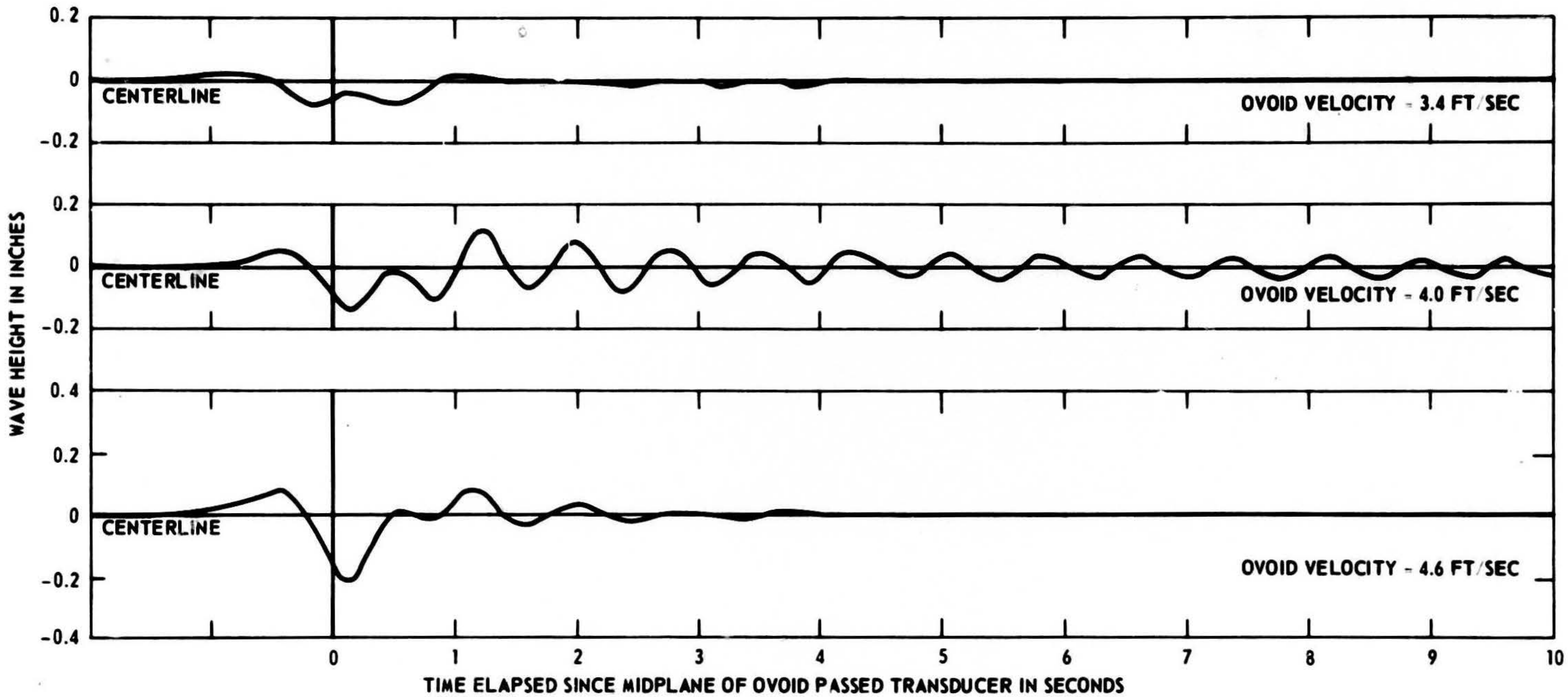


Figure 16 – Centerline Wave Heights of a Rankine Ovoid Towed at 3.4, 4.0, and 4.6 Feet per Second

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, Measuring Station 4.

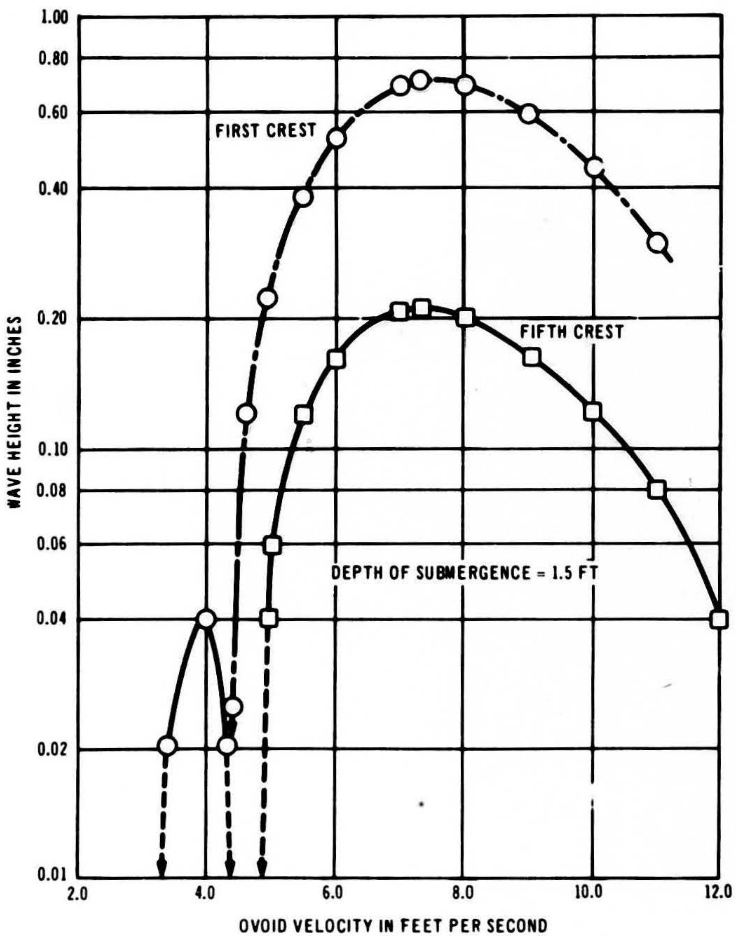


Figure 17 – Centerline Wave Heights as Functions of Ovoid Velocity

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, Measuring Station 4.

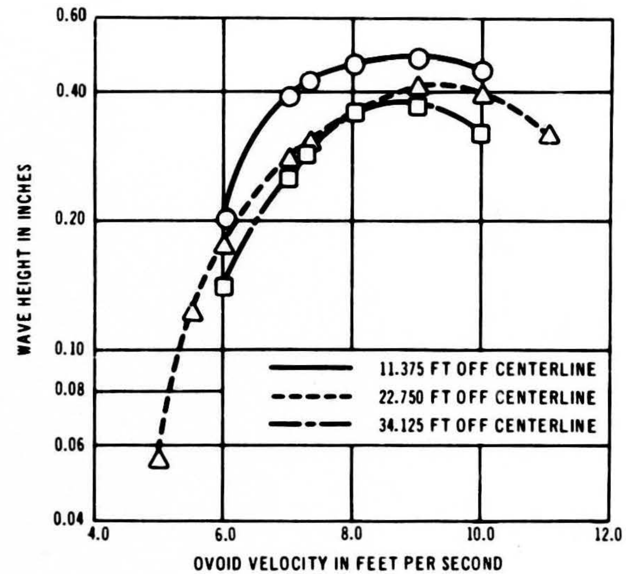


Figure 18 – Maximum Off-Centerline Wave Heights as Functions of Ovoid Velocity

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, Measuring Station 4.

Since the wave pattern forms a V in the wake, the wave crests off the centerline build up some distance aft of the model. The wave heights reach a maximum value and then decay slowly downstream. The wave heights of the highest crests at each athwartship station are plotted in Figure 18 as a function of towing speed.

Irregularities in the wave structure in Figures 10 through 16 result from the wave interference between the source and sink of the Rankine ovoid singularity representation. This interference is particularly noticeable in the off-centerline wave profiles at the higher towing speeds. At the very low speeds shown in Figure 16, the centerline wave profile is very irregular immediately behind the model.

The length of the steady-state wave train increased with the distance the model traveled from the starting point to the measuring station. Figure 19 shows the growth of the steady-state wave pattern at one towing speed as the measuring station is moved farther and farther from the starting point. The longest steady-state wave profile was obtained at Measuring Station 4. Measuring Station 5 was 187 ft from the start of the run, and the model had stopped before all of the wave train reached the wave transducer. The deceleration of the model may have produced spurious surface disturbances.

DISCUSSION OF RESULTS

Although a complete wave analysis is not available at the Model Basin for comparing measured wave height with theory, certain quantative observations can be made from the measured wave heights. A limited portion of the wave train on the centerline can be compared with stationary-phase theory. Since two similar ovoid models were tested, it is also possible to evaluate the accuracy of Froude scaling.

STATIONARY-PHASE WAVE PROFILES

Stationary-phase wave profiles computed from Equation [4] for several of the centerline wave conditions are compatible with the wave measurements which Livingston obtained in a coordinate system which moved with the model. Figure 20 compares one of his wave profiles obtained with the 9-ft Rankine ovoid with the stationary-phase waveform. With this large model, there was only a short interval between the first and third wave crest where the theory showed good agreement with the experimental results.

The stationary-phase wave profile in Figure 19 is superimposed on the experimental data obtained with the 4.5-ft ovoid at four measuring stations over the length of the run. Although these experimental data were not obtained in a moving coordinate system, it is evident that a steady-state wave pattern was set up which increased in length as the measuring station is moved away from the starting point. In the steady-state portion of the wave profile, the stationary-phase analysis showed reasonable agreement with experiment up to the first wave crest.

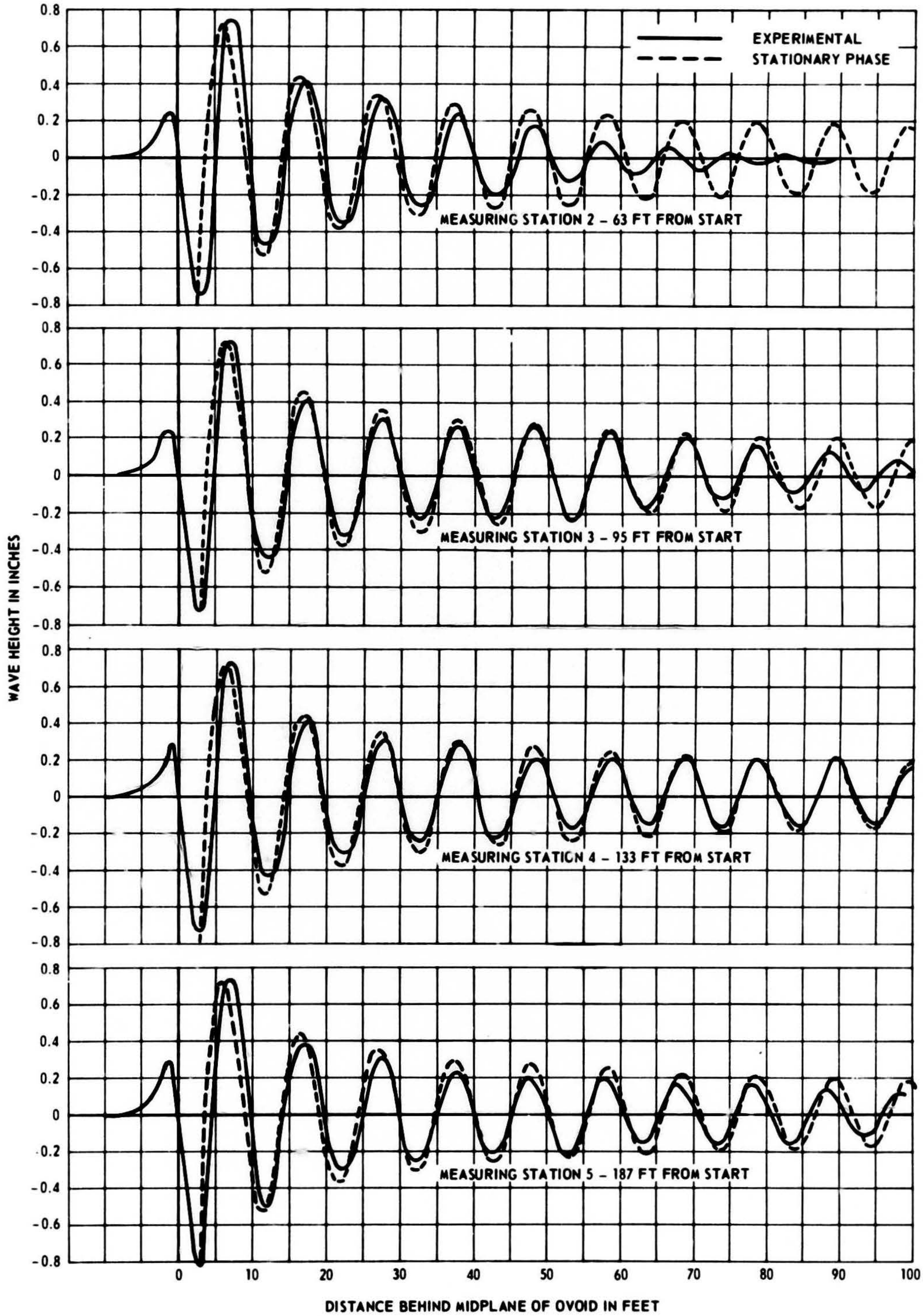


Figure 19 – Growth of the Centerline Wave Profile for Different Lengths of Run Compared with Stationary-Phase Expression

Ovoid length = 4.5 ft, submergence depth = 1.5 ft, U = 7.3 ft/sec, F_f = 1.05.

FROUDE NUMBER SCALING EFFECTS

Since Livingston's ovoid was 9 ft long and was towed at a depth of 3 ft, it was postulated that a 4.5-ft ovoid towed at a depth of 1.5 ft would yield similar results. Therefore, if tests were run at the same Froude number, the body should be towed at $1/\sqrt{2}$ times the former velocity. The ensuring wave heights would then be one-half as high. Absolute values of the dimensionless wave heights of the first centerline wave crests from the two sets of data are plotted as functions of depth Froude number in Figure 21. Superimposed on these data is a theoretical curve obtained from the stationary-phase analysis. The small differences may be attributed to viscous effects, secondary wave effects, and inadequacies of the source-sink representation of the body in proximity to a free surface.

In Figure 22, data obtained with the 4.5-ft model have been converted to conditions for a 9-ft model using Froude scaling. There are two sets of curves which compare the wave profiles of the 4.5- and 9-ft Rankine ovoids at Froude numbers 1.4 and 1.005. As in Figure 21, there was reasonably good agreement over the steady-state portion of the wave profile.

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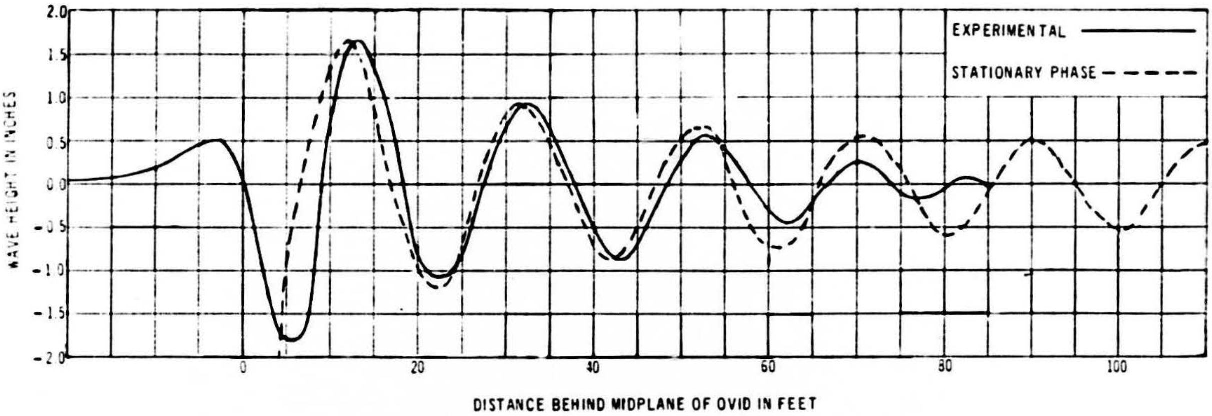

Figure 20 – Centerline Wave Profile Obtained in a Moving Coordinate System Compared with Stationary-Phase Expression

Ovoid length = 9 ft, submergence depth = 3 ft, U = 10 ft/sec, F_f = 1.02.

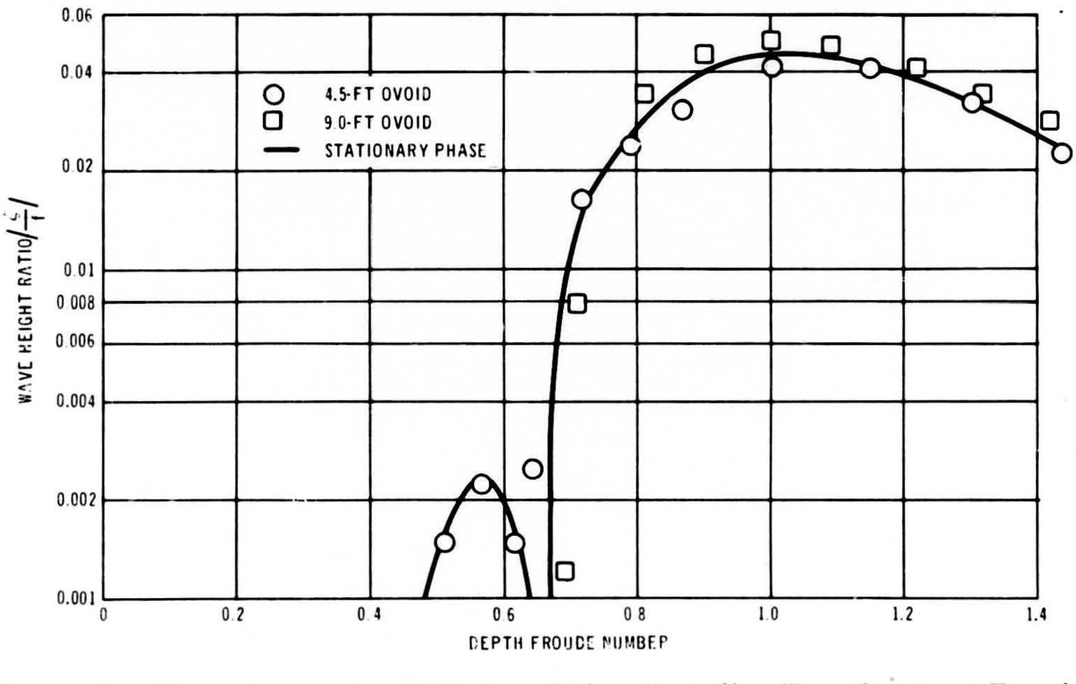

Figure 21 – Dimensionless Wave Heights of First Centerline Wave Crests as Functions of Depth Froude Number – Experimental and Stationary-Phase Data

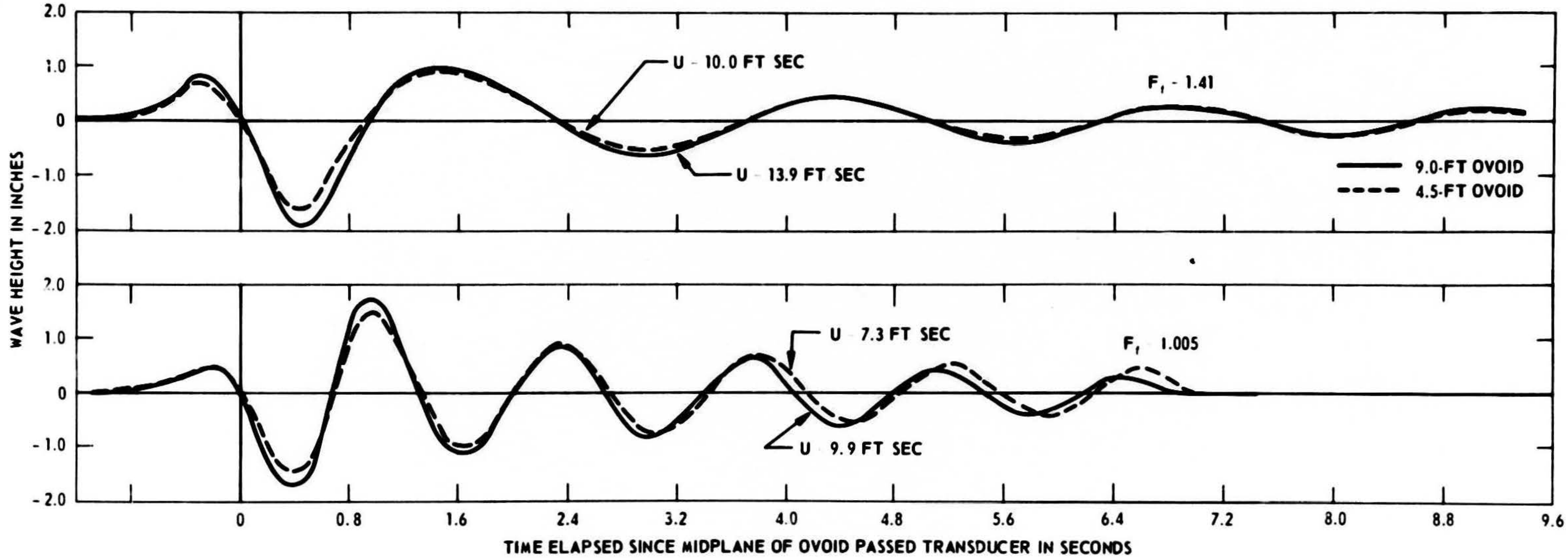

Figure 22 – Froude Scaling of Centerline Wave Heights of the 4.5- and 9-Foot Rankine Ovoids

The data for the 4.5-ft ovoid are scaled to the flow conditions of the 9-ft ovoid at a submergence depth of 3 ft and the same Froude number.

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Two Rankine ovoids were towed beneath the surface of a large body of water at several speeds and depths. The surface disturbance was measured both on and off the centerline of travel. The results of these tests were then compared with existing theoretical wave height predictions.

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